HOLOCENE GLACIAL VARIABILITY RECORDED IN LAKE SEDIMENTS FROM NEVADO HUAGURUNCHO, PERU

Senior Thesis

Submitted in partial fulfillment of the requirements for the

Bachelor of Science Degree

The Ohio State University

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December, 2012

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ABSTRACT

Glaciers and lakes are recorders of high altitude climate changes, and these archives are important in our understanding of past global changes. This study aims to provide further insight into how temperature and precipitation varied in the past, and combined to drive glacial variability in the tropical Andes of South America. A percussion core was taken in the field at Lake Yanacocha located in the watershed of Nevado Huaguruncho, Peru. Bulk density was measured along the profile of core and the chronology was determined by measuring radiocarbon on macrofossil samples within the sediments. The core geochemistry was analyzed using scanning X-Ray Fluorescence (XRF), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and coulometry. Changes in clastic sediment concentrations in the Yanacocha sediment core are represented by shifting values of Ti, K, bulk density, organic carbon, and residual flux. High clastic sediment values characterize the early Holocene, followed by low values during most of the early stages of the mid-Holocene, at a time the lake sediments suggest there was a period of more arid conditions. There is a notable increase in clastic sediments starting at the end of the mid-Holocene, and again during the late Holocene. This study, when paired with other similar research, further improves our knowledge of the timing and causes of climate variability in the tropical Andes, and suggests that glaciers during the Holocene advanced at times of both colder and wetter conditions.

ACKNOWLEDGMENTS

I would like to thank the funding organizations for providing me the resources to conduct this project:

National Science Foundation, Paleo Perspectives on Climate Change division
The Ohio State University Climate, Water and Carbon Program
The Keck Geology Consortium
The Mayers Undergraduate Research Scholarship at The Ohio State University

Also, I would like to thank everyone that helped me along the way, especially my research advisor and mentor at The Ohio State University, Dr. Nathan Stansell, who included me in his research project and taught me more than I could have learned in any classroom. Also, I want to thank Dr. Don Rodbell at Union College and Dr. Bryan Mark at The Ohio State University for graciously including me in their research projects.

I would like to thank my parents, Tom and Pat Sedlak, for their love and support along the way the last four and a half years.

I would like to thank The Ohio State University for providing me four and a half fantastic years of education. I especially want to thank all the faculty and staff in the School of Earth Sciences and my academic advisor, Dr. Anne Carey for steering me in the right direction.

INTRODUCTION

Glaciers and lakes record high altitude climate changes, and these archives are important in our understanding of past global changes (Abbott et al., 2003; Rodbell et al., 2009). More records of climate variability are needed because they provide evidence of tropical ocean-atmospheric interactions that are critical components of the global climate system. Thus, more records from the tropical Andes, in particular, need to be obtained to better document past shifts in temperature and the regional hydrologic cycle. Additionally, the climate of Peru is sensitive to tropical Pacific, tropical Atlantic, and North Atlantic influences. It would thus be beneficial to obtain better records of glacial changes from the Central Andes that provide insight into high altitude temperature and precipitation during the Holocene, linked to both high and low climatic variability (Baker et al., 2001).

The ice margins of the tropical Andes fluctuated in response to climatic changes during the Holocene (Rodbell et al., 2009). This resulted in sediments within the glacier being expelled and deposited into the lakes below. Sediment cores taken from these lakes provide records of glacial advances and retreats (Nesje et al., 2001). These glaciers also deposit sediment and leave glacial landforms on the landscape surrounding the lake itself. The resulting landforms provide another tool for determining the glaciers extent and its timing when paired with sediment core data (Rodbell et al., 2009; Stansell et al., 2010). Sediment cores from other Central Andean pro-glacial lakes highlight the potential of these systems to contain records of continuous up-valley glacial fluctuations that can be dated. Andean lakes have also recorded precipitation variability in the tropics over the Holocene (Polissar et al., 2006; Rodbell et al., 2008; Seltzer et al., 2000; Stansell et al., 2010). When combined with glacial records, these existing paleoclimate records contain valuable information about the timing and pattern of climatic fluctuations throughout the Holocene.

This study aims to provide further insight into how temperature and precipitation varied in the past and combined to drive glacial variability. Specifically, new sediment core data from pro-glacial Lake Yanacocha on the eastern front of the Peruvian Andes are presented to reconstruct the regional Holocene climate history. The addition of this sediment core from the tropical Andes will help refine the chronology of the glacial events in the region. This archive will also be compared to other nearby paleoclimate records in order to better determine the timing and causes of Holocene climate variability in the tropical Andes.

STUDY SITE

Lake Yanacocha and Geology of the Region

The targeted study site was in a catchment below a glaciated peak in the Western Cordillera of the Peruvian Andes. It is important to understand the geology of the catchment because the sediments that accumulate in the lake basin are eroded from the bedrock and transported directly into the basin. Identifying the sources of the sediments helps to understand the glacial processes that have taken place over recent history. The Andes Mountains are comprised of old marine sedimentary rocks that have been uplifted during orogeny events. Pre-Mesozoic rocks compose the underlying, basement layer of the stratigraphy. The oldest unit in the sequence is composed of Pre-Cambrian to Upper Paleozoic units of schists, slates and phyllites. Overlying those is Upper Triassic to Lower Jurassic sections which are dominated by shales and limestone. The

Cretaceous section contains various sedimentary rocks, particularly shales, greywackes, and intercalated volcanic rocks.

Lake Yanacocha (10°33.590 S, 75°55.815 W, 4,360 m a.s.l.; Fig. 1) is located on the relatively wet eastern slope of the Central Peruvian Andes in valley watershed adjacent to Nevado Huaguruncho. The lake was cored from its depocenter which measured 21.65m. It sits below one of the peaks of Nevado Huaguruncho which measures 5,010m a.s.l. and is dominated by quartz monzonite igneous bedrock, of Tertiary age. Above the quartz monzonite stratigraphic layer lays the Marañon Formation, of Neoproterozoic age. The Marañon Formation consists of fine grained shales, as well as metamorphosed schists and phyllites, primarily of brown to gray coloration.

Modern Climate

The Peruvian Andes modern climate is as expected of a low-latitude mountainous region. Often in high elevation, low-latitude regions daily temperature variability is great, which is seen in the tropical Andes. Generally the precipitation in the Andes comes from the trade winds carrying moisture from the Tropical Atlantic Ocean. The precipitation over the South American continent is affected by the sea surface temperature interaction with the tropical air. The eastern edge of the Andes, or windward side, where Lake Yanacocha is located, generally receives more precipitation than the leeward, western side of the range. The location of the Intertropical Convergence Zone (ITCZ) effects the seasonal precipitation that is brought over in the easterly trade winds over the Amazon Basin from the Atlantic Ocean. The ITCZ is the location where the trade winds of the northern and southern latitudes meet, and follows the seasonal pattern of solar declination. At this latitude the sea surface temperatures are relatively warm, causing convection in the northern and southern Hadley Cells and increased cloud cover and precipitation within the ITCZ. The ITCZ, however, is an oceanographic feature, and changes in precipitation over land in these regions are ultimately affected by the strength of South American Summer Monsoon (SASM). The SASM is affected by the ITCZ, but precipitation patterns in these regions are driven by a more complex interaction of land-sea influences and moisture recycling over the Amazon Basin. Moisture levels over the South American continent can also be affected from the Pacific Ocean side through El Niño Southern Oscillation activity.

METHODS

Geochronology

Radiocarbon age dating is a tool used to provide age-depth models for sediment cores, ranging from 40k years B.P to a few hundred years B.P. Radiocarbon is produced in the atmosphere by cosmic ray bombardment with Nitrogen, and living organism's uptake it later. When an organism dies, it ceases to metabolize ^{14}C any longer and decay begins. These organisms are then transported and deposited, generally by surface runoff or fluvial activity into the lake environment, and are trapped in the sediment deposits on the lake bottom.   Samples of the macrofossils are extracted from cores and pretreated to be run on an Accelerated Mass Spectrometer. The AMS provides an age for the fossil in the record and by combining multiple ages from the same core an age-depth model for the sediment core can be produced which is essential for further analyzing the sediment cores.

The sediment chronology of Lake Yanacocha was determined by measuring radiocarbon on 7 aquatic macrofossil samples from the sediment core. Samples were picked using jeweler's tweezers under a binocular dissecting microscope. These samples were pretreated at the University of Pittsburgh using standard acid-base-acid protocols. The acid-base-acid pretreatment is used in order to eliminate Calcium Carbonate from the bedrock and date the organic matter that is in the sample. The first step is to decalcify the sample by treating it with 0.5 N HCl for 30 minutes on heat, which is repeated until the remaining solute is clear. This is done to remove the Calcium Carbonate from the sample which is desired because it is essential to only date the organic Carbon. After the residual solute is clear the sample is rinsed back to neutrality. Next, the sample is treated with 0.5% KOH for 60 minutes on heat and is repeated until the solute is clear in order to remove the soil humics, and rinsed to neutral. The base treatment (KOH) can introduce atmospheric CO_2 so another acid treatment is required to rid the sample of the CO_2. Finally the sample is rinsed to neutral with deionized water and the pH is tested. If the pH is not a neutral 7, then the sample must continuously be rinsed until the sample is neutral (Abbott and Stafford, 1996). The pretreated samples were then measured at University of California, Irvine using accelerated mass spectrometry. The CALIB version 6.0 was used to convert the radiocarbon ages to calendar ages (present defined as 1950 A.D.). The median ages represent the maximum likelihood values exported from the Intcal09 dataset (Reimer et al., 2009). Depths were converted to ages using a 2nd order polynomial fit between the median ages (R^2=0.99) (Table 1 and Fig. 2).

Fieldwork, Sedimentology and Geochemistry

The Nesje percussion core system is a lightweight, transportable system that can be used for extracting sediment cores out of high elevation pro-glacial lakes. The system consists of a polycarbonate tube up to six meters in length for capturing sediments, paired with a core head which is pounded by a weight into the underlying sediment. Both the core head and weight are attached to static ropes which are connected to the frame resting on the coring platform. The system requires three people to operate and is a quality system for high elevation coring because it is easy to transport. The Nesje coring system is better than traditional coring systems because it can obtain uninterrupted sediment cores up to six meters in length, and is not limited to use in shallow water. The Nesje system does not have a defined water depth limit, however the extraction of the core from the lake bottom becomes more difficult in water depths greater than 60 meters. Overlapping sediment was taken from the depocenter of Lake Yanacocha that was sounded using a Garmin® fish finder GPS. Another percussion core was taken in order to capture the sediment-water interface and be paired with the other percussion cores. The top 25 cm of the surface core was extruded into plastic sample bags in the field at 0.25cm intervals. The percussion cores were shipped to The Ohio State University where they were further processed.

Sedimentology of the cores was analyzed at the Mercer Sedimentology Laboratory at the Byrd Polar Research Center at The Ohio State University. In the lab, sediment cores were split vertically into working and archive halves. Cores were then described for Munsell color and major sedimentological features. Cores were also digitally photographed using a DMT CoreScan

II at 40pixel/mm resolution. Bulk density was sampled over 1 cm intervals, every 2 cm down-core.

Lake Yanacocha's sediment core geochemistry was measured using multiple methods. The core was analyzed using an X-Ray Fluorescence (XRF) instrument, ITRAX, (Croudace et al., 2006) at the Large Lakes Observatory at the University of Minnesota, Duluth. The core was measured for XRF at 1mm resolution using a 10 second exposure time for each interval. The ITRAX scanner is fitted with three main instruments for taking measurements of sediment cores. The first is the optical camera system, which is used to provide high quality digital images of the core, in particular a high resolution image of where each measurement is taken. Next, the X-Ray generator is used to emit X-Rays to the core which excites different elements at different voltages and gives a fingerprint of each element down core. The final piece of equipment is an X-Ray line camera that records the intensity of radiation given off by each interval (Croudace et al., 2006). The surface samples were also analyzed at 0.5cm intervals every 2cm of the core which was extruded into plastic sample bags. Surface sediments were measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and sent to ALS Minerals commercial facility in Reno, Nevada where they were analyzed. The samples were pulverized to a size <75μm and then measured using 48 element four acid ICP-MS. Finally, scanning XRF data (CPS values) were converted to concentration (%) using linear regression.

Coulometry of the core was measured to record the content of organic carbon, calcium carbonate, and residual flux in the lake every 5-10cm (Dean, 1999; Englemann et al., 1985). Combustion of samples at 1000°C in a UIC 5200 furnace was used to determine total carbon

(TC). Total inorganic carbon (TIC) was measured using a UIC 5240 acidification module by acidifying samples in 1.0N $HClO_4$. In both cases, carbon dioxide is released and recorded using a UIC Coulometrics™ carbon dioxide coulometer in the Core Analysis Laboratory at Union College. Total organic carbon was calculated as a weight percentage by subtracting TIC from TC (TOC=TC-TIC). Total organic matter (TOM) was then calculated as 1.724*TOC, and the residual values were determined by subtracting TOM and calcium carbonate from 100. Finally, residual flux was determined as the percent residual values multiplied by BD and the accumulation rate of each respective interval in the sediment core (cm/yr) (Fig. 3).

Clastic sediment flux (defined as g cm^{-2} yr^{-1}) is a measure of the accumulation rate of detrital material in a depositional system. Flux also takes into account bulk density variations that are important when considering dilution effects. For proglacial lake systems, calculating clastic sediment flux provides insight into the relationship between erosion rates and up-valley glacial activity of the region. In closed basin systems the glacier activity erodes the surrounding bedrock directly into the lake system. Thus, flux can be calculated and used to interpret the extent of glacial activity in the region when the glacier was present. The calculation requires measured values of the sedimentation rate (cm yr^{-1}), bulk density of the sediment (g cm^{-3}), total organic matter (which is calculated from the total organic Carbon) and the weight fraction of calcite which is calculated from total organic Carbon. Higher clastic sediment flux values typically represent periods of advancing glaciers and lower values represent ice retreat.

RESULTS

Changes in clastic sediment concentrations in the Yanacocha core are represented by shifting values of Ti, K, bulk density, organic carbon, and residual flux. Concentration data for the elements Ti and K are the focus here because these elements represent the major sediment sources in Lake Yanacocha's watershed. Namely, higher clastic sediment values are characterized by relatively high concentrations of Ti, K, residual flux and dry bulk density (>0.4g cm^{-3}), accompanied with low values of organic carbon (Fig. 3). Low clastic sediment occurrences are characterized by high concentrations of organic carbon teamed with low relative values of Ti, K, residual flux and bulk density (<0.4g cm^{-3}).

Carbon and calcium carbonate content in sediment cores can help provide insight into regional hydrologic balance. Calcium carbonate and organic carbon values were at or near 0% in the core until the beginning of the Mid-Holocene low-stand ~8,000 cal yr BP. At ~7,000 cal yr BP a sharp spike occurs with up to ~50% calcium carbonate and ~7% organic carbon values. This peak is followed by a decrease in calcium carbonate and carbon values until they again reach 0% at ~1,500 cal yr BP (Fig. 3).

The sediment core is characterized by multiple transitions of clastic sediment concentrations throughout it. For example, the period between 13,000 cal yr BP and 12,050 cal yr BP contain decreasing values of clastic sediments, and this interval of values is at or near the lowest levels shown on the entire core. This decrease in clastic sediments is followed by sustained low values until 10,300 cal yr BP. After this lull, an increase in clastic sediments occurred from 10,300 until 9,300 cal yr BP. The time span from 9,300 to 5,000 cal yr BP has a trend of low clastic sediment values overall, however, decadal to centennial scale fluctuations in clastic sediment values. Nevertheless, the stretch of time 5,000 to 1,750 cal yr BP is characterized by a general increase in concentration of clastic sediment values with a step-wise transition to lower values from ~4,500 to 3,500 cal yr BP, but the overall trend is toward higher values. However, the interval from 1,750 to 650 cal yr BP is characterized by a distinct shift toward lower values of clastic sediments, while the period from 650 to 100 cal yr BP rebounds back to higher values (Fig. 3).

DISCUSSION

Clastic sediment variability can be interpreted in order to understand changes in glacial mass-balance. When glaciers are growing, they actively erode the surrounding landscape and provide increases in clastic sediment fluxes. A decrease in clastic sediment flux is a result of a lull in glacial activity and decreased erosion rates (Harbor and Warburton, 1993). Changes in glaciers are affected by changes in precipitation and temperature. When conditions in the Andes are cold and/or wet, glaciers tend to advance causing increased clastic sediment flux. During arid and/or warm periods, clastic sediment flux decreases because of the decrease in erosion rates.

The project at pro-glacial Lake Yanacocha is just one in a series of projects attempting to reconstruct past climate in the tropical Andes. The Yanacocha site represents the easternmost glaciated watershed in the Peruvian Andes in the study and also bears a relatively low headwall. Lake Yanacocha has seen less glacial activity than most of the other regional records, because it has a lower headwall than the other peaks in the regions. It is thus important to discuss Lake Yanacocha in terms of the other regional records and to compare everything on a regional scale.

After the geochemical analyses were completed the data had to be analyzed to understand the glacial processes involved. Increases in the sediment flux are interpreted as enhanced glacial activity. The greater rate of clastic sediment accumulation comes from the increased deposition from the glacier. Consistently low values of clastic sediment flux, Ti and K represent a lull in glacial activity and erosion. High values of Calcium Carbonate and Organic Carbon are representative of drier periods. Drier periods in closed basin lake systems, like Lake Yanacocha, provide for decreased lake levels and the potential to precipitate out Calcium Carbonate and Organic Carbon.

The Early Holocene 10,300 to 8,000 cal yr BP

The transition from the Late Glacial Stage to the Early Holocene is well captured in the Yanacocha lake sediment record. Following a period of low clastic sediment values at the end of the Late Glacial Stage, the Yanacocha sediment record contains tentative evidence of an Early Holocene advance between 10,300 and 9,300 cal yr BP (Fig. 3). Similarly, Rodbell (1992) and Röthlisberger (1987) reported data showing early Holocene glacial advance in the Cordillera Blanca using lichenometric and radiocarbon dated moraines (Rodbell et al., 2009). More recently, Licciardi et al. (2009) documented evidence of an early Holocene advance in the Cordillera Vilcabamba using cosmogenic dating methods. Thus, combined with our Yanacocha record, there is provisional evidence of early Holocene glaciations in multiple valleys in the Peruvian Andes. However, another regional record, the ice cores from the Huascaran glacier characterize the early Holocene as dry and warm (Thompson et al., 1995), contrary to the Yanacocha record. Following the purported advance from 10,300 to 9,300 cal yr BP there was a decrease in clastic sediments in Yanacocha from 9,300 to 7,000 cal yr BP indicating the beginning of a period low glacial activity.

The Middle Holocene 8,000 to 3,700 cal yr BP

The middle Holocene period in the Lake Yanacocha record was generally an interval lacking in glacial activity. There is no clear evidence in Yanacocha of any mid-Holocene glacial advance from 7,000 to 5,000 cal yr BP. Clastic sediments then increase in the period from 5,000 to 4,200 cal yr BP. This corresponds to the rapid ice growth on the Quelccaya Ice Cap that began ~5,000 cal yr BP, followed by wetter and/or cooler conditions for the remaining Holocene (Buffen et al., 2009). A trend toward wet, cool conditions is also shown in the Huascaran record (Thompson et al., 1995). This shift from relatively dry to wet conditions is also apparent in the Yanacocha record, with high calcium carbonate values peaking at ~7,500 cal yr BP, followed by decreasing values for the remaining middle and late Holocene. This can also be seen in the Oxygen isotope work done by Seltzer et al. (2000) in the Lake Junin (Fig. 4) record suggesting a trend towards wetter conditions in the region. In addition, in Rowe et al. (2002) organic carbon shows an increase in the lake level at Lake Titicaca, also insinuating wetter conditions. Also, it was mentioned by Rodbell et al. (2009) there may be evidence of a mid-Holocene glacial advance as seen in the lichenometric and radiocarbon ages recovered. From 4,200 to 3,700 cal yr BP clastic sediments were relatively low in the Yanacocha core. Therefore, conditions in the region were wetter overall (Rowe et al., 2002) however clastic sedimentation rates did not spike implying precipitation does not solely affect glacial activity.

The Late Holocene 3,700 BP to present day

Clastic sedimentation rates in the late Holocene did not remain in a lull as they had been in the mid-Holocene. There was a trend toward higher clastic sediment values between 3,700 and 1,750 cal yr BP, which was also an interval of wet conditions in the Lake Titicaca region (Rowe et al., 2002). Then, from 1,750 to 700 cal yr BP a decrease in the clastic sediments was seen in Yanacocha. This decrease in clastic sediments began approximately 750 years before the start of the Medieval Climate Anomaly (MCA) which corresponds to the decrease in Sr concentration values in the Lake Queshquecocha record (Stansell et al., in review) (Fig. 4). (Bird et al., 2011) found O18 values in the late Holocene to be some of the highest of the entire Holocene, indicating an arid interval. From 600 to 200 cal yr BP it is seen in Yanacocha to be a period of increased glacial activity, which corresponds with the Little Ice Age (LIA). Additionally, the Quelccaya Ice Cap recorded a cold and wet interval from 450 to 230 cal yr BP and a cold and dry phase from 230 to 70 cal yr BP (Thompson et al., 1986; Liu et al., 2005). A wet phase during the LIA is seen in the oxygen isotope records that were taken from the Huascaran ice cap and Lake Pumacocha, Peru (Fig. 4). Lake levels as recorded by Rowe et al. (2002) also indicate increased lake levels from ~500 cal yr BP to present day. The increased appearance of clastic sediments in Yanacocha during this period follows suit with other proxies to signify a correspondence between the Lake Yanacocha sediments and wetter conditions and cooling temperatures in the region.

Holocene Climate Change in the Tropical Andes

Some similarities among the Holocene climate change proxies in the Peruvian Andes are apparent, however, notable differences occur as well. The sediment core from Lake Yanacocha provided clastic sediment data that lacked glacial activity during most of the middle Holocene. (Thompson et al., 1995) suggest based on the Huascaran ice core record that temperature in the region progressively cooled through the Holocene, that should have led to improving conditions for glacial advance. The Yanacocha record suggests that glaciers were in a retreated state during much of the Holocene (Fig. 3). A reason for this parody between (Thompson et al., 1995) and the Lake Yanacocha record could be because the headwall above Lake Yanacocha is much lower than any of the other proxies from the region and the conditions may not have been ideal for glacier formation at the Yanacocha site. (Bird et al., 2011) found what is interpreted as a precipitation record at nearby Lake Pumacocha, while the Calcium Carbonate and Organic Carbon signals at Lake Yanacocha showed the middle Holocene to be an arid period. There is no explanation at this time to explain the aridity during the middle Holocene at Lake Yanacocha. There is evidence of the ITCZ shifting south (Haug et al., 2001), which has the potential to create greater volumes of precipitation over the South American continent however the data from Yanacocha does not show increased precipitation. The emergence of more frequent El Niño Southern Oscillation events at ~5,000 cal yr B.P. (Moy et al., 2002) could have an effect on precipitation and temperature in South America during the middle Holocene. In addition, solar variability, greenhouse gas concentrations, North Atlantic influences and many other climate processes could have affected glaciers and lake level changes in the Andes during the Holocene.

CONCLUSION

The Lake Yanacocha sediment core records fluctuating ice margins during periods of shifting climate during the Holocene. In general for Peru, glacial advances during the Holocene occur at times of cold and/or wet conditions, whereas dry and/or warm periods are characteristic of ice retreat. Specifically, there is evidence for a glacial advance in the Yanacocha watershed during the early Holocene. More records are needed, however, in order to determine the scale and magnitude of Early Holocene climate variability. Furthermore, the mid-Holocene is characterized primarily by decrease in glacial activity at Lake Yanacocha prior to ~5,000 cal yr BP, during a period of pronounced aridity. Thus, evidence for a lake level low-stand at Yanacocha coincides well with the arid mid-Holocene that has been documented in other nearby paleoclimate regional sediment records during the same interval. Consequently, the early part of the mid-Holocene was a period of overall restricted ice cover and more arid conditions in the Yanacocha watershed followed by renewed glaciation later, leading into the late Holocene. Additionally, a period of pronounced ice retreat just prior to the local LIA is apparent in Yanacocha and multiple regional records. These records also identify a consistent pattern of colder and wetter conditions during the LIA. Although many of the paleoclimate records available from Peru show similar changes during the Holocene, differences in the individual archives are apparent and can be attributed to small regional variations in both climate forcing and response of local geomorphic systems. The Yanacocha sediment record provides new evidence of Holocene glacial variability, and more archives of its type are needed to further understand paleoclimate systems.

SUGGESTIONS FOR FUTURE WORK

The Lake Yanacocha project is one in a series of many projects that were used to help construct Holocene climate in the tropics. Other sediment cores have been taken from different proglaical lakes in the region to better understand what was going on during the Holocene. However, more cores are needed to improve the quality and resolution of climate variability in the tropics. Suggestions for future work include obtaining more sediment cores from proglaical lakes in the tropics in order to improve the quality of the existing data. Also, other analyses of geomorphology can help in the reconstruction of past climate, such as dating of glacial moraines surrounding these proglaical lakes, to recognize when the glaciers were at which locations.

Figures

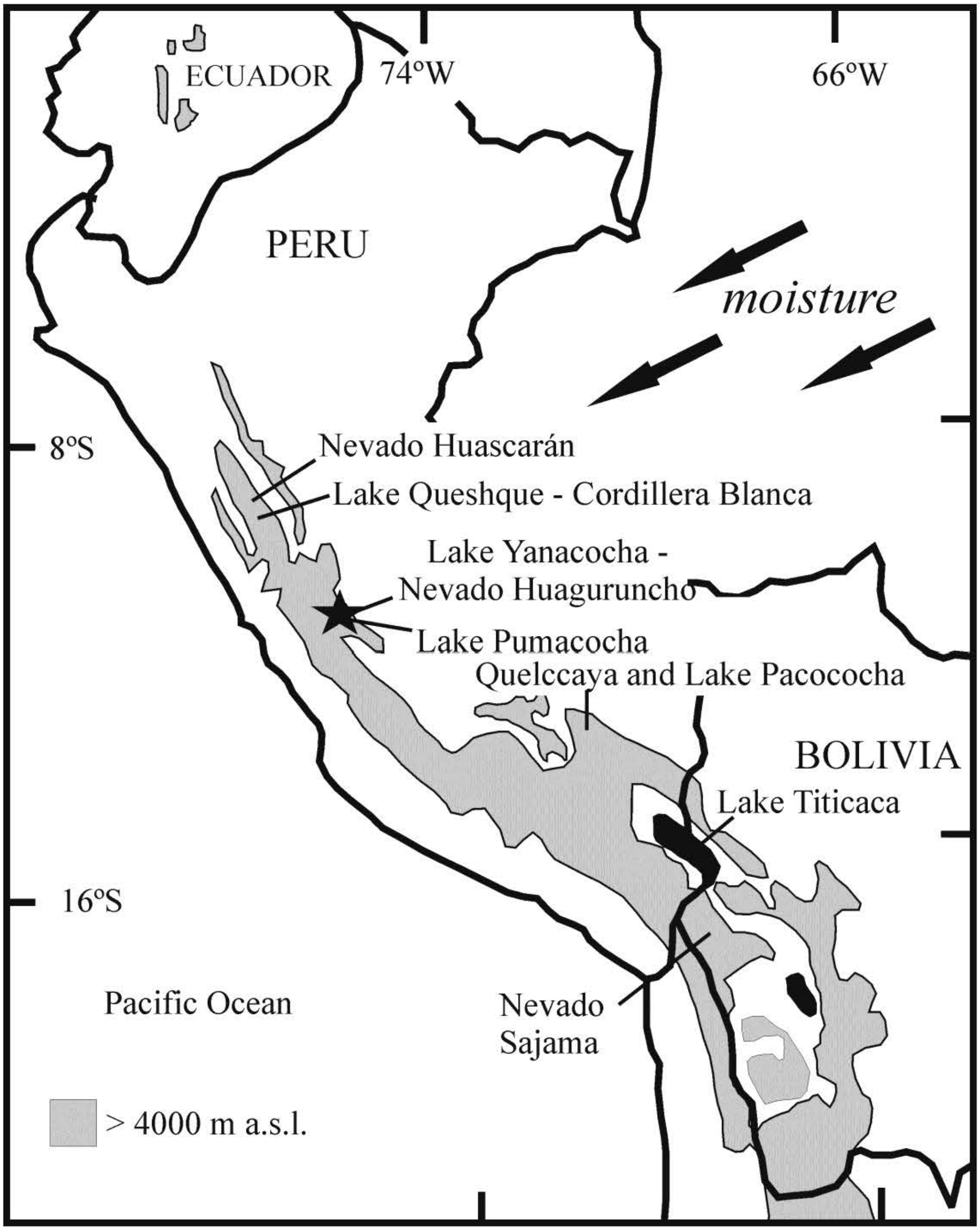

Figure 1. Location map of sites mentioned in the text. Lake Yanacocha is on a west-facing slope of Nevado Huaguruncho in the Peruvian Andes.

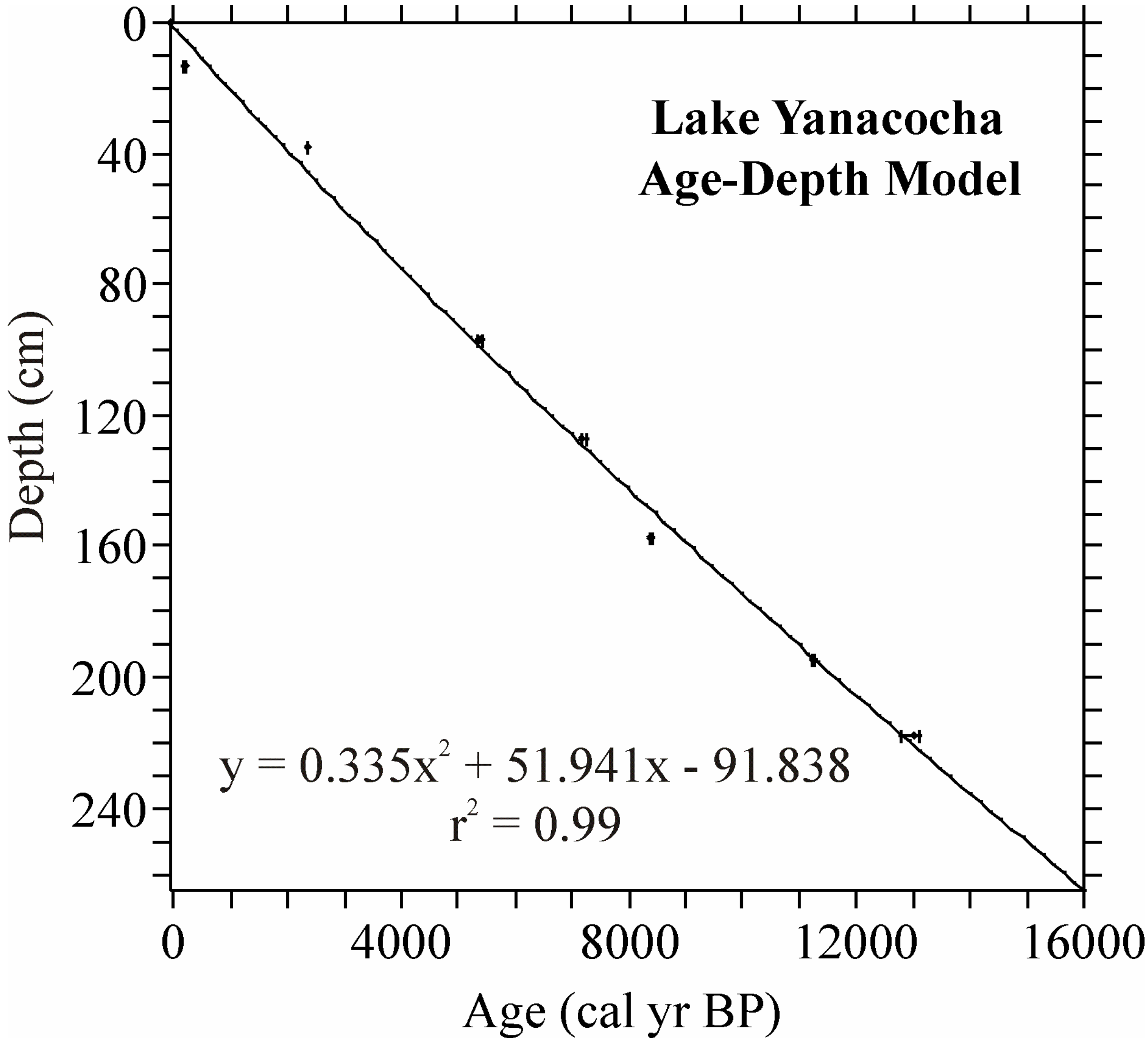

Figure 2. Lake Yanacocha age-depth model (data in Table 1). Depth values were converted to age using a 2nd order polynomial.

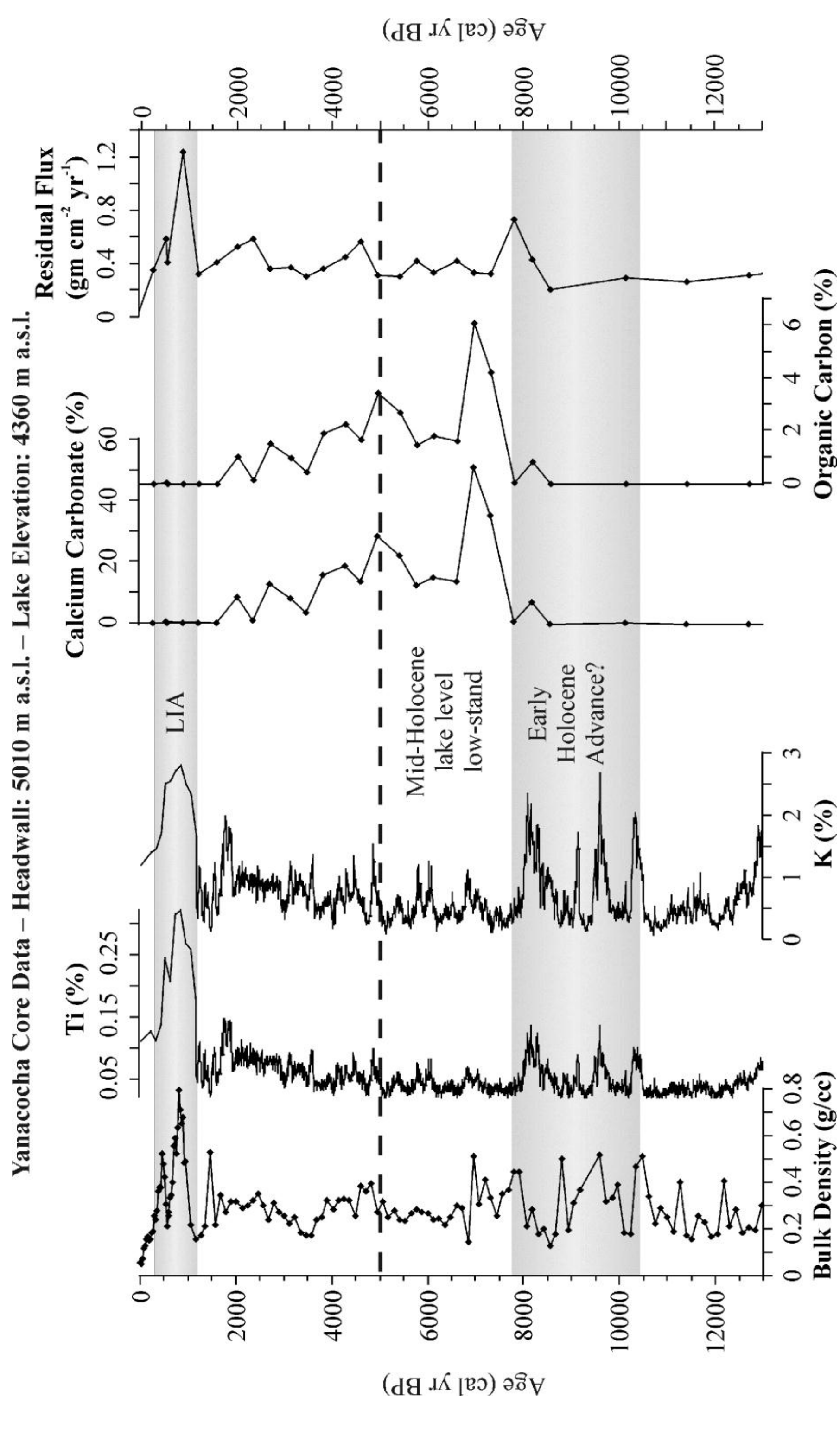

Figure 3. The Yanacocha sediment core data plotted versus age.

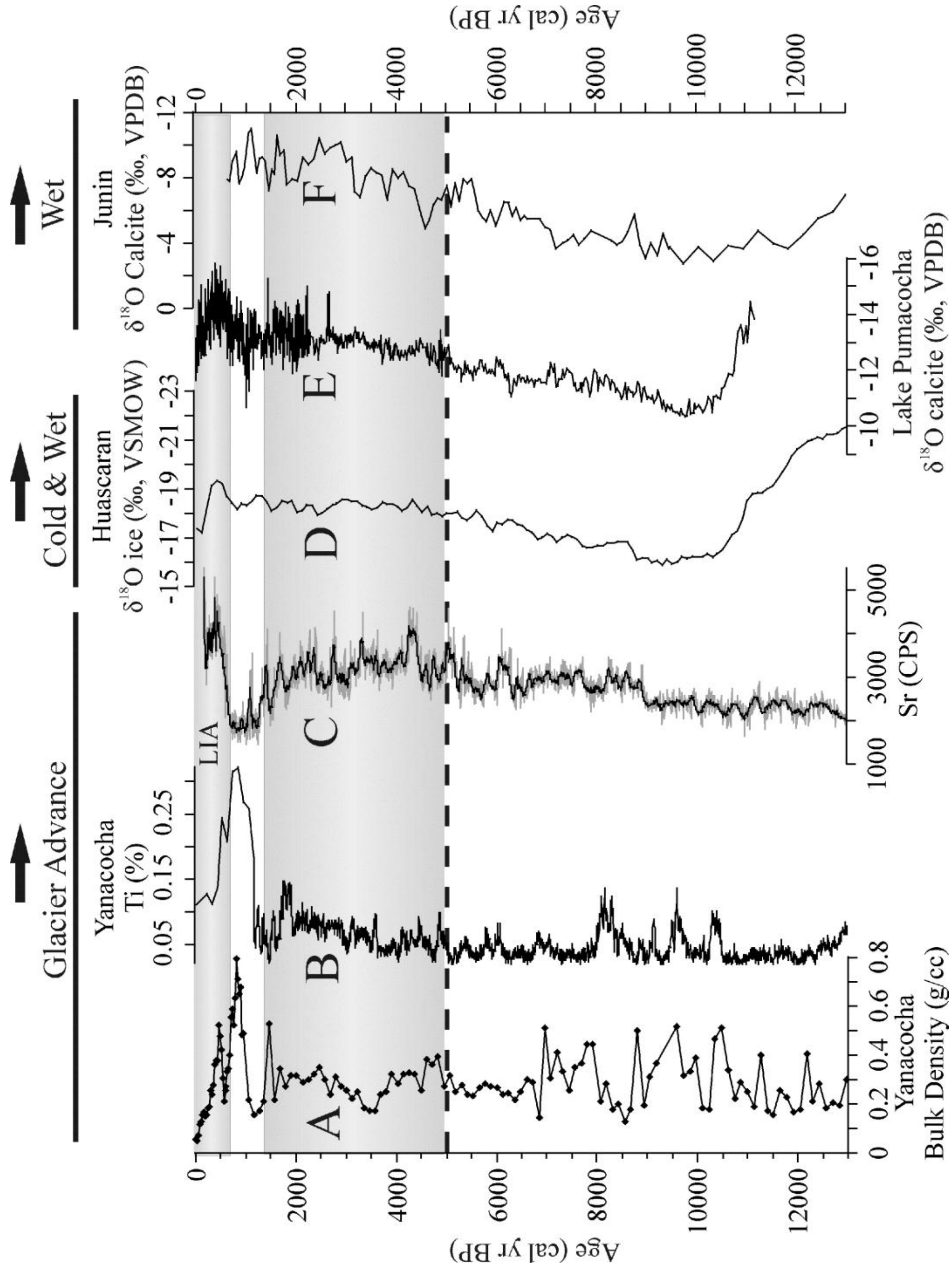

Figure 4. Yanacocha sediment core data (A-B) plotted versus regional paleoclimate records. High values of clastic sediments in the Yanacocha record correspond to periods of increased glaciation in the Cordillera Blanca (C-D). Glaciers generally advanced in Peru during the Holocene at times of colder and wetter conditions (E-F). The dashed line indicates the timing that multiple regional records from the region identify a shift from relatively warm and dry conditions during the early Holocene, to cold and wet conditions in the late Holocene.

Table

Lab #	Depth (cm)	^{14}C Age	Measured error (±)	1σ calibrated age
UCI-101317	13	165	15	168-(190)-220
UCI-101392	38	2345	15	2340-(2350)-2456
UCI-101393	97	4685	20	5322-(5390)-5419
UCI-101319	127	6235	20	7155-(7190)-7250
UCI-101394	157	7580	20	8370-(8390)-8413
UCI-101320	195	9865	20	11220-(11250)-11278
UCI-101395	218	11100	25	12806-(13000)-13119

Table 1. Radiocarbon ages measured on aquatic macro-fossils used in study. The median ages represent the maximum likelihood median ages exported from CALIB version 6.0 and the IntCal 09 dataset. The error bars represent the 1-sigma error range.

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